Real-Time Condition Monitoring of Propulsion Systems Through High-Performance Computing

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MSFC is responsible for the testing and diagnosis of both current and future NASA propulsion systems including the Space Shuttle Main Engine (SSME) and the Redesigned Solid Rocket Motor (RSRM). During the development of the SSME, significant progress has been made within NASA and across the aerospace community in improving the diagnostic evaluation of high-frequency dynamic data. Fast and reliable evaluation of such data is crucial to the Space Shuttle Operations Program since such study is invaluable in preventing catastrophic engine hardware failures. Moreover, reliable engine system diagnostic evaluations can extend the scheduled maintenance intervals for major engine components such as high-speed turbopumps. Such dynamic assessment is very challenging due to the computational and manpower intensive nature of the dynamic signatures taken from various engine locations. Current SSME dynamic data processing and evaluation is done post-flight or following ground test (at both engine and component level), with a typical diagnostic turnaround time of 1 or 2 days. This “diagnostic lag time” must be eliminated if real time diagnosis of engine systems is ever to become a reality. A true real-time condition monitoring system must be capable of acquiring great volumes of high-frequency data containing complex and frequently subtle dynamic attributes which then must be successfully analyzed for correct test article diagnosis. The health monitoring system must utilize conventional signal processing, recently developed dynamic signal classification technology (i.e. nonlinear signal analysis), dynamic data compression/extraction methods, and unsupervised statistical classification methods. Development of such a real-time condition health monitoring system which effectively integrates dynamic data attributes is very challenging due to data bandwidth requirements, algorithm computational intensity, and cross-channel communications. However, the expected savings and improvement in overall real-time diagnostic capabilities make the development effort well worthwhile.

Even with the significant improvements in propulsion system dynamic data evaluation methods achieved over the past decade within the NASA/contractor community, there exists a great potential for advancement in the performance of the health monitoring function. The dynamic data evaluation function must be improved upon by:

- Reducing overall propulsion system diagnostic turnaround time;
- Cutting analysis manpower requirements;
- Including complex (i.e. nonlinear) dynamic data attributes in every diagnostic assessment;
- Eliminating end-to-end data processing discrepancies/variances at remote end users;
- Implementing dynamic indicators from test articles as on-line test control “redlines”; and
- Ending reliance on analog tape data backup.

In brief, NASA/MSFC’s next generation dynamic data analysis system must be faster, better, and cheaper than its predecessor in order to become an integral part of a total real-time health monitoring system.

In an effort to overcome the limitations of current dynamic data acquisition, reduction, and evaluation efforts within the NASA/MSFC community, both short- and long-term goals have been identified. In the short term, a real-time dynamic data system capable of simultaneously acquiring at least 100 channels of high-frequency data with an initial analysis bandwidth of 20 kHz must be developed. This baseline system must be capable of extracting conventional dynamic attributes (i.e. power spectral density (PSD) domain indicators) from the monitored signals. These recovered attributes from the input data channels, along with raw-time varying signals, must be available for real-time display, test control, and immediate post-test analysis. Moreover, all data must be immediately archived for further post-test processing and trend analysis efforts. With the successful implementation of the baseline large-scale digital signal processing (LDSP), system efforts will then focus on the integration of recently developed signal processing “tools” which draw pertinent, yet subtle dynamic attributes from the monitored high-frequency data channels. A majority of these “tools” involve nonlinear signal analysis, which has consistently proven invaluable in failure mode identification. The nonlinear “tools” effectively exploit hidden nonlinear phase relationships within the spectra of acquired high-frequency dynamic data. These relationships are key in determining signal structures indicative of propulsion system/system component fault modes. Finally, with the successful integration of all dynamic data signal processing “tools” (including both conventional and nonlinear analysis) into the real-time LDSP system, efforts will be focused on integrating generated test article dynamic performance parameters with traditional operational parameters (i.e. pressures, temperatures, flow rates) into one comprehensive health monitoring system. Such an effort will not only rely on the effective extraction of the complex dynamic data attributes in real-time but also their compression and statistical classification.

NASA/MSFC has been provided an exceptional opportunity in working with the Air Force community in the development of a real-time LDSP system for the monitoring and analysis of propulsion article high-frequency dynamic data. Through an intra-agency technology utilization agreement, Arnold Engineering and Development Center (AEDC) has agreed to share with

NASA/MSFC the technology associated with its highly successful computer assisted dynamic data monitoring and analysis system (CADDMAS) used in the support of gas turbine engine testing. CADDMAS effectively utilizes high-performance computing technology in performing real-time dynamic data acquisition and reduction. In return, NASA has agreed to share all resulting system upgrades resulting from the integration of MSFC diagnostic code to the baseline CADDMAS. Hopefully, the AEDC community will find the updates useful in their diagnosis of flight hardware along with their plant support equipment. Moreover, the NASA/MSFC dynamic data analysis community is fortunate in having the opportunity to work with the enabling software technology behind the CADDMAS solution. This technology contained in the multigraph architecture (MGA) developed by the Measurement and Control Systems Laboratory of Vanderbilt University[1] has been of great value to MSFC in the integration of proven NASA/MSFC diagnostic "tools" into the baseline CADDMAS. Key aspects of MGA, such as the structural adaptivity of the execution environment, a necessity for a real-time health monitor, are very important to NASA/MSFC. Key features of the MGA which underlay CADDMAS are allowing for substantial cost savings in the conversion of NASA/MSFC diagnostic code to the already proven test support system.

As previously discussed, NASA/MSFC is integrating high-frequency dynamic data diagnostic code into CADDMAS. Digital signal processing code, including both conventional and recently developed nonlinear applications,[2,3] have been successfully executed in real-time. Complex high-frequency analysis tools such as synchronous tracking and bicoherence are currently being used online to support SSME advanced turbopump development efforts. Such tools are invaluable in determining specific hardware failure modes such as turbomachine rolling element bearing flaws or cavitation via induced oscillations in propellant pumps.

In summary, high-performance computing can open the "bottleneck" associated with the evaluation of propulsion system high-frequency diagnostic data. NASA/MSFC, AEDC, and Vanderbilt University are converging on a cost-effective solution for an online condition health monitoring system which combines high-performance/distributed processing computing technology and MSFC-developed diagnostic expertise. Currently, a prototype version is successfully supporting SSME alternate high-pressure fuel turbopump development efforts at both the full-scale engine hot-fire and component test level.

[1]Sztipanovits, J.; Wilkes, D.; Karsai, G.; Biegl, C.; Lynd, L.: "The Multigraph and Structural Adaptivity." IEEE Transactions on Signal Processing, vol. 41, no. 8, August 1993, pp. 2695–2716.

[2]Jong J.; Jones J.; Jones P.; Nesman T.; Zoladz T.; Coffin T.: "Nonlinear Correlation Analysis for Rocket Engine Turbomachinery Vibration Diagnostics." 48th Meeting of the Mechanical Failure Prevention Group (MFPG), April 1994.

[3]Jong, J.; Jones, J.; McBride, J.; Coffin, T.: "Some Recent Developments in Turbomachinery Fault Detection." NASA 1992 Conference on Advanced Earth-to-Orbit Propulsion Technology, May 1992.

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University/Other Involvement: Arnold Engineering and Development Center (USAF); Vanderbilt University (Measurement and Controls Systems Laboratory)

Biographical Sketch: Tom Zoladz is an engineer working in the Fluid Dynamics Analysis Branch of the Structures and Dynamics Laboratory of Marshall Space Flight Center. He supports the characterization of unsteady flow environments within several of the propulsion systems under supervision and development at MSFC. Some current tasks include the analysis of a cavitation induced oscillation in the SSME high-pressure fuel turbopump and characterization of combustion stability in advanced hybrid rocket motors. He graduated from the University of Tennessee in 1987 with a B.S. in mechanical engineering.

Tony Fiorucci is an aerospace engineer with the Structural Dynamics and Loads Branch of the Structures and Dynamics Laboratory at Marshall Space Flight Center. He specializes in evaluation and characterization of vibration environments for both flight- and ground-test propulsion systems supervised by MSFC. His current and primary tasks include assessment/qualification of all vibration data acquired in support of the development, certification, and flight programs for the Space Shuttle Main Engine Project. Fiorucci graduated with a B.S. in engineering mechanics from the University of Tennessee in 1988.